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NEW MARINE ΔR VALUES FOR THE SOUTH PACIFIC SUBTROPICAL GYRE REGION

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ABSTRACT. This paper presents 31 new ΔR results of known-age, pre-AD 1950 shells from the South Pacific subtropical gyre region, spanning from the Tuamotu Archipelago in the east to New Caledonia in the west. This doubles the number of available ΔR values for the Oceania region. These values indicate that the regional offset (ΔR) from the modeled radiocarbon marine age has remained relatively constant over the last 100 yr prior to 1950. Variation from the norm can be attributed to various influences including localized upwelling around islands, the presence of a hardwater effect, direct ingestion of old carbon by the live shellfish, or enhanced exchange with atmospheric CO_2 as a consequence of photosynthetic activity or increased aeration.

INTRODUCTION

The surface ocean (down to around 200 m depth) has an apparent radiocarbon age that is, on average, 400 yr older than associated materials from the terrestrial (atmospheric) reservoir. This is known as the marine reservoir effect. It is caused both by a delay in ^{14}C exchange between the atmosphere and ocean, and by the mixing of surface waters with upwelled, ^{14}C-depleted deep ocean water (Stuiver et al. 1986). This reservoir effect is automatically corrected for when a marine shell conventional radiocarbon age (CRA)[6] is calibrated using the modeled marine ^{14}C calibration curve (e.g. Marine04: Hughen et al. 2004), which represents a global average of the surface ocean ^{14}C as it changes over time. The calibration of marine samples is complicated by local and regional deviation from this global average. To account for this deviation, a local correction factor, or ΔR—the difference between the modeled ^{14}C age of surface water and the actual ^{14}C age of surface water at that locality—needs to be determined (Stuiver et al. 1986). This can be calculated from marine samples from known locations collected prior to AD 1950, whose age of death is known precisely (i.e. annually banded corals, shells and/or otoliths of surface dwelling fish) (e.g. Kalish 1993; Dye 1994; Guilderson et al. 2000; Petchey et al. 2004) or from contemporaneous terrestrial/marine samples typically from archaeological deposits (e.g. Reimer et al. 2002; Ulm 2002; Jones et al. 2007) or tephra deposits that act as onshore/offshore isochrons (Sikes et al. 2000).

Data collected over the last decade (see the Marine Reservoir Database [Reimer and Reimer 2005]) suggest that ΔR values from pre-AD 1950 marine proxies in the Pacific vary significantly across the region. A recent assessment of these values by Petchey (in press) highlights a number of shortcomings with extant ΔR values, including questionable collection dates, the dating of unsuitable species, and limited provenance information. This limited number of reliable ΔR values is a problem for researchers trying to obtain accurate calibrated results of marine shell and other animals that subsisted on marine resources (e.g. human [Petchey and Green 2005; Nunn et al. 2007a,b]; Pacific rat [Anderson et al. 2001], pig [Beavan Athfield et al. 2008], or turtle bone [Petchey 2001]).

In this paper, we address this problem for the marginal southwest Pacific and central East Polynesia, specifically French Polynesia (i.e. Society Islands, Marquesas Islands, Tuamotu Archipelago, Gam-

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[6] A conventional radiocarbon age (CRA) is obtained from a ^{14}C measurement following the conventions set out by Stuiver and Polach (1977).

bier Islands, and the Austral Islands), the Cook Islands, Vanuatu Islands, Fiji, New Caledonia, Santa Cruz Islands, Tongan Archipelago and the Samoan Archipelago. To this end, we present 31 new ΔR values obtained from known-age, pre-AD 1950 marine shells and compare these to extant published values from this region (see Figure 1 and Table 1).

METHODOLOGY

^{14}C dating of marine organisms whose calendar date of death is well documented enables comparison of the atmospheric and marine ^{14}C contents at a specific time and location. This comparison necessitates that samples selected for analysis conform to a number of prerequisites as laid out in Petchey (in press):

1. The marine sample must have been collected live, or the date of death independently validated. For "historic," known-age shells, this can best be demonstrated by museum documentation, the presence of fleshy remains of an animal, or valves in articulation with intact ligaments.
2. The geographic location where the samples were collected must be known.
3. The marine sample must be identified to genus level (preferably species), and the dietary and habitat preferences of that species must closely represent that of the reservoir being investigated (e.g. open ocean, estuarine, etc.).
4. For museum specimens, the date of collection must be known and be before AD 1950 (i.e. prior to detonation of thermonuclear devices, which added ^{14}C into the atmosphere). This "bomb effect" shows up in coral core records from the North Pacific as early as 1956 (Konishi et al. 1982) and 1957 in the South Pacific (Toggweiler et al. 1991; Druffel and Griffin 1993).

Suspension feeders (also known as filter feeders) were preferentially selected for this research as these typically consume suspended phytoplankton and dissolved inorganic carbon from seawater, and are usually considered the most reliable shells for ^{14}C dating because they more closely reflect the ^{14}C content of the ocean mixed surface layer (Forman and Polyak 1997; Hogg et al. 1998). Even with these suspension-feeding shellfish, the effect of different sources of ^{14}C depends upon the degree of water exchange with the open ocean, ocean circulation, and the habitat and diet of the marine animal investigated (Tanaka et al. 1986; Hogg et al. 1998; Petchey et al. 2004). In a couple of instances, carnivorous shellfish have also been dated. Little information is available for carnivorous shellfish, but they are presumed to show an averaging effect depending on the carbon reservoirs of their prey and could, therefore, be subject to similar uncertainties as their prey. In these situations, the analysis of oxygen and carbon stable isotopes in combination with ΔR data can be used to distinguish between different environmental influences on marine shell (Culleton et al. 2006; Petchey et al. 2008). In particular, δ^{18}O is a highly sensitive indicator of change in water temperature and salinity, while the δ^{13}C value of marine shells is thought to predominantly reflect changes in water source and overall marine productivity (Keith et al. 1964; Killingley and Berger 1979; Kennett et al. 1997). The effect of ingestion of limestone by herbivores and deposit-feeding species is well documented (Dye 1994; Anderson et al. 2001), and these species were not sampled.

New samples for ΔR analysis were obtained from mollusk collections housed at the Australian Museum, National Museum of New Zealand, Auckland War Memorial Museum (New Zealand), and the Museum of Natural History (Paris). In some cases, museum documentation was incomplete or ambiguous. It was necessary, therefore, to obtain independent support from published sources for the collection date and geographic sampling location, in addition to evidence that the shells were collected live. This information is given in Appendix 1. This kind of information is often lacking for extant published ΔR values; therefore, less confidence can be placed in these values (Petchey, in press).

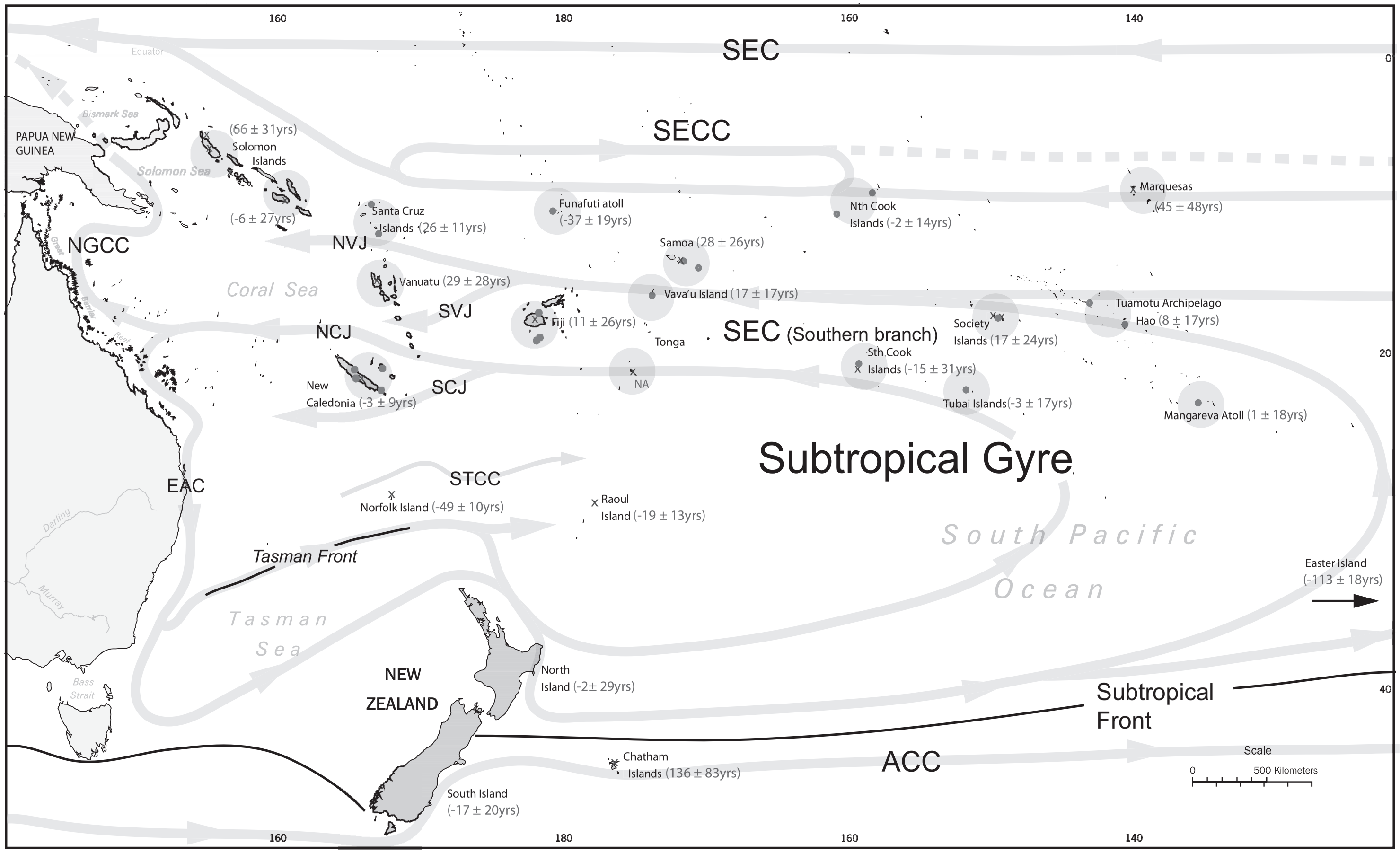

Figure 1 Map showing average ΔR value for each island group given in Table 1, and location of shell samples (both extant published results [x] and new ΔR results presented in this paper [gray circles]). Major oceanic currents within the South Pacific Ocean after Tomczak and Godfrey (2001:111) and Ganachaud et al. (2007:8, Figure 4). Abbreviations: NVJ – North Vanuatu Jet; SVJ – South Vanuatu Jet; NCJ – North Caledonian Jet; SCJ – South Caledonian Jet; SEC – South Equatorial Current; SECC – South Equatorial Counter Current; EAC – East Australian Current; NGCC – New Guinea Coastal Current; STCC – Subtropical Counter Current; ACC – Antarctic Counter Current.

Table 1 ΔR results of shells analyzed and regional averages. Shaded = extant published ΔR values (data from Reimer and Reimer 2005). Excludes data from Norfolk Island, Kermadec Islands, Chatham Island, and New Zealand.

										Regional average ΔR			
Region	Specific location	Sample material[a]	Date of collection	δ^{13}C ‰ (±0.2)	δ^{18}O ‰ (±0.06)	^{14}C age & error (BP) [Rs(t)]	Marine modeled age [Rg(t)][b]	ΔR (yr) [Rs(t) – [Rg(t)]	χ^2 test	ΔR pooled + error (E)	$\chi^2/(n-1)$	ΔR with external variance	Lab #[c]
Austral Islands	Unknown	Isognomonidae: *Isognomon legumen* (FF)	1932	3.38	–1.41	452 ± 17	455 ± 23	–3 ± 17	—	–3 ± 17	—	—	Wk-20349
Easter Island	Easter Island	Coral: *Porites lobata*	1950	—	—	355 ± 18	469 ± 24	–113 ± 18	—	–113 ± 18	—	—	AA-series
Fiji	Kadavu, Tevuki	Cardiidae: *Fragum unedo* (FF)	Apr 1952?	2.22	–0.66	456 ± 19	469 ± 24	–13 ± 19	$\chi^2_{3:0.05}$ = 13.06<7.81	11 ± 8	4.35	11 ± 26	Wk-21057
	Ono Island, Vabea	Conidae: *Conus* sp. (C)	1933	1.81	–1.02	440 ± 19	456 ± 23	–16 ± 19					Wk-21058
	Viti Levu, Ellington	Chamidae: *Chama* sp. (C)	Oct 1919	2.46	–0.88	431 ± 19	449 ± 23	–18 ± 19					Wk-21056
	Viti Levu	Coral	1945	—	—	507 ± 12	464 ± 23	43 ± 12					L-series
Gambier Arch.	Mangareva Atoll, Vaiatekeue Is.	Pteriidae: *Pinctada maculata* (FF)	Feb 1903	2.98	–0.29	473 ± 19	447 ± 23	26 ± 19	$\chi^2_{2:0.05}$ = 3.23<5.99	1 ± 11	1.62	1 ± 18	Wk-19677
	Mangareva Atoll	Pteriidae: *Pinctada margaritifera* (FF)	Sept 1903	2.82	–0.07	445 ± 20	447 ± 23	–3 ± 20					Wk-19678
	Tearia Bank 18 m	Chamidae: *Chama pacifica* (FF)	Nov 1904	1.99	–0.66	426 ± 19	448 ± 23	–22 ± 19					Wk-21061
Marquesas[d]	Anaho Bay, Nuku Hiva	Coral	1950 midpoint	—	—	514 ± 48	469 ± 24	45 ± 48	—	45 ± 48	—	—	AA-series
New Caledonia (including Loyalty Islands)	Presqu'ile Ducos, Noumea	Veneridae: *Gafrarium tumidum* (FF)	1903/4?	1.80	–1.08	443 ± 17	447 ± 23	–4 ± 17	$\chi^2_{5:0.05}$ = 5.03<11.07	–3 ± 9	1.01	No variance	Wk-20336
	Poindimié	Pectinidae: *Laevichlamys squamosa* (FF)	Apr/Aug 1950	0.96	–1.53	437 ± 17	469 ± 24	–32 ± 17					Wk-20341
	Paines des Gaiacs	Veneridae: *Tapes literatus* (FF)	Jul 1943	0.79	–0.48	470 ± 19	462 ± 23	8 ± 19					Wk-21055
	"Loyalty Island"	Conidae: *Conus arenatus* (C)	1926?	3.18	–0.70	473 ± 19	452 ± 23	21 ± 19					Wk-21059
	Unknown	Veneridae: *Venus peupera* (FF)	~1876[e]	1.66	–2.03	490 ± 45	475 ± 23	15 ± 45					Wk-8046
	Unknown	Veneridae: *Venus reticulata* (FF)	~1876[e]	2.46	–1.86	480 ± 45	475 ± 23	5 ± 45					Wk-8047

Table 1 ΔR results of shells analyzed and regional averages. Shaded = extant published ΔR values (data from Reimer and Reimer 2005). Excludes data from Norfolk Island, Kermadec Islands, Chatham Island, and New Zealand. *(Continued)*

										Regional average ΔR			
Region	Specific location	Sample material[a]	Date of collection	δ^{13}C ‰ (±0.2)	δ^{18}O ‰ (±0.06)	^{14}C age & error (BP) [Rs(t)]	Marine modeled age [Rg(t)][b]	ΔR (yr) [Rs(t) – [Rg(t)]	χ^2 test	ΔR pooled + error (E)	χ^2/ (*n*–1)	ΔR with external variance	Lab #[c]
Northern Cook Islands	Manihiki	Cardiidae: *Fragum fragum* (FF)	1924	3.64	–0.16	459 ± 19	451 ± 23	8 ± 19	$\chi^2_{1:0.05}$ = 0.58<3.84	–2 ± 14	0.58	No variance	Wk-19676
	Penrhyn atoll	Pteriidae: *Pinctada margaritifera* (FF)	1931	1.34	–1.62	442 ± 20	455 ± 23	–13 ± 20					Wk-19691
Samoan Arch.	Tutuila Is., Faga'itua	Cardiidae: *Fragum fragum* (FF)	1933	2.98	–0.51	460 ± 19	456 ± 23	4 ± 19	$\chi^2_{5:0.05}$ = 5.74<11.07	28 ± 10	1.15	28 ± 26	Wk-19682
	Tutuila Is., Pago Pago	Veneridae: *Antigona reticulata* (FF)	Jul 1865	2.57	–1.44	500 ± 20	480 ± 23	20 ± 20					Wk-19683
	'Upolu, Fagola	Cardiidae: *Fragum fragum* (FF)	1922	2.87	–0.99	481 ± 17	450 ± 23	31 ± 17					Wk-20343
	'Upolu?	Turbinidae: *Turbo petholatus* (H)	1882	2.03	–2.46	550 ± 40	474 ± 23	79 ± 40					Wk-6383
	'Upolu?	Strombidae: *Strombus pacificus* (H)	1882	2.05	–0.88	500 ± 40	474 ± 23	29 ± 40					Wk-6384
	'Upolu?	Strombidae: *Strombus lentiginosus* (H)	1882	3.19	–2.06	560 ± 40	474 ± 23	89 ± 40					Wk-6385
Santa Cruz/ Reef Islands	Reef Island	Cardiidae: *Fragum fragum* (FF)	Jul/Aug 1926	2.36	–0.69	457 ± 21	452 ± 23	5 ± 21	$\chi^2_{2:0.05}$ = 1.46<5.99	26 ± 11	0.73	No variance	Wk-19689
	Reef Island, Pileni Island	Isognomonidae: *Isognomon isognomon* (FF)	Jul/Aug 1926	3.01	–1.18	482 ± 19	452 ± 23	30 ± 19					Wk-21065
	Vanikoro	Carditidae: *Beguina semiorbiculata* (FF)	Jul/Aug 1926	2.87	–1.00	489 ± 17	452 ± 23	37 ± 17					Wk-20344
Society Islands	Tahiti, Outumaoro	Archidae: *Barbatia* sp. (FF)	Jun 1919	2.85	–1.22	472 ± 19	449 ± 23	23 ± 19	$\chi^2_{5:0.05}$ = 4.52<11.07	17 ± 9	0.91	17 ± 24	Wk-19684
	Tahiti, Taravao, under stones	Archidae: *Barbatia* sp. (FF)	Jul 1919	3.11	–1.54	446 ± 20	449 ± 23	–3 ± 20					Wk-19685
	Tahiti, Papeete	Muricidae: *Drupa ricinus* (C)	Jun 1919	0.17	–0.72	453 ± 19	449 ± 23	4 ± 19					Wk-21060
	Tahiti, Taravao	Isognomonidae: *Isognomon* sp. (FF)	Jul 1919	3.17	–0.58	471 ± 17	449 ± 23	22 ± 17					Wk-20348

Table 1 ΔR results of shells analyzed and regional averages. Shaded = extant published ΔR values (data from Reimer and Reimer 2005). Excludes data from Norfolk Island, Kermadec Islands, Chatham Island, and New Zealand. *(Continued)*

										Regional average ΔR			
Region	Specific location	Sample material[a]	Date of collection	$\delta^{13}C$ ‰ (±0.2)	$\delta^{18}O$ ‰ (±0.06)	^{14}C age & error (BP) [Rs(t)]	Marine modeled age [Rg(t)][b]	ΔR (yr) [Rs(t) – [Rg(t)]	χ^2 test	ΔR pooled + error (E)	$\chi^2/(n–1)$	ΔR with external variance	Lab #[c]
	Moorea	Turbinidae: *Turbo setosus* (H)	1883	—	—	553 ± 42	471 ± 23	82 ± 42					L-576K
	Tahiti	Turbinidae: *Turbo setosus* (H)	1957	—	—	515 ± 42	469 ± 24	46 ± 42					L-576E
Solomon Islands (North)	Bouganville	Conidae: *Conus* sp. (C)	1944	2.12	–2.16	480 ± 40	463 ± 23	17 ± 40	$\chi^2_{2:0.05}$ = 2.46<5.99	66 ± 24	1.23	66 ± 31	Wk-8381
	Teop Island, Bouganville	Archidae: *Anadara antiquita* (SF)	1933	3.13	–1.78	560 ± 45	456 ± 23	104 ± 45					Wk-8380
	Vella Lavella Island	Muricidae: *Chicoreus ramosus* (C)	1930?	3.83	–2.10	540 ± 40	454 ± 23	86 ± 40					Wk-7828
	Malaita, Fauabu	Psammobiidae: *Asaphis violascens* (DF)	1932	0.96	–2.07	590 ± 55	455 ± 23	135 ± 55	Excluded from regional average because deposit-feeding species				Wk-8382
	Ufa, Russell Islands	Psammobiidae: *Asaphis violascens* (DF)	1945	1.71	–1.83	680 ± 50	464 ± 23	216 ± 50	Excluded from regional average because deposit-feeding species				Wk-8383
Solomon Islands (South)	Guadalcanal Island	Coral (*Porites australiensis*)	1950	—	—	463 ± 27	469 ± 24	–6 ± 27	—	–6 ± 27	—	—	CAMS-series
Southern Cook Islands	Mangaia Island, reef	Conidae: *Conus* sp. (C)	1954?	–0.95	–0.38	688 ± 20	469 ± 24	219 ± 20	$\chi^2_{3:0.05}$ = 102.12<7.81	Excluded from regional average because of hardwater effect			Wk-21062
	Mangaia Is.	Conidae: *Drupa ricinus* (C)	1924	2.03	–0.54	400 ± 30	451 ± 23	–51 ± 30		–15 ± 13	2.83	–15 ± 31	Wk-21983
	Rarotonga Is.	Pteriidae: *Pinctada margaritifera* (FF)	Oct/Nov 1931	1.68	–0.95	466 ± 17	455 ± 23	11 ± 17					Wk-20340
	Rarotonga Is., 18 m depth	Coral: *Porites lutea*	1953	—	—	417 ± 27	469 ± 24	–52 ± 27		($\chi^2_{2:0.05}$ = 5.66<5.99)			CAMS-series
Tongan Arch. (North)	Vava'u Island	Isognomonidae: *Isognomon isognomon* (FF)	Jul 1865	3.21	–0.51	497 ± 17	480 ± 23	17 ± 17	—	17 ± 17	—	—	Wk-20346
Tongan Arch. (South)	Pangaimotu, Tongatapu	Archidae: *Anadara antiquata* (FF)	1926	1.39	—	295 ± 68	452 ± 23	–157 ± 68	$\chi^2_{1:0.05}$ = 5.89<3.84	Excluded from regional average due to enriched CO_2			ANU-6421
	Havelu, Tongatapu (lagoon)	Veneridae: *Gafrarium tumidum* (FF)	1926	–0.25	—	539 ± 74	452 ± 23	87 ± 74		Excluded from regional average due to hardwater effect			ANU-6420

Table 1 ΔR results of shells analyzed and regional averages. Shaded = extant published ΔR values (data from Reimer and Reimer 2005). Excludes data from Norfolk Island, Kermadec Islands, Chatham Island, and New Zealand. *(Continued)*

										Regional average ΔR			
Region	Specific location	Sample material[a]	Date of collection	$\delta^{13}C$ ‰ (±0.2)	$\delta^{18}O$ ‰ (±0.06)	^{14}C age & error (BP) [Rs(t)]	Marine modeled age [Rg(t)][b]	ΔR (yr) [Rs(t) – [Rg(t)]	χ^2 test	ΔR pooled + error (E)	$\chi^2/(n–1)$	ΔR with external variance	Lab #[c]
Tuamotu Arch.	Marutea Sud Atoll[f]	Pteriidae: *Pinctada margaritifera* (FF)	Dec 1903	0.76	–0.51	400 ± 21	447 ± 23	–47 ± 21	$\chi^2_{1:0.05}$ = 4.14<3.84	Excluded from regional average due to closed lagoon/enriched CO_2 effect			Wk-19690
	Hao, on reef	Spondylidae: *Spondylus anacanthus* (FF)	Nov 1904	2.12	–0.99	456 ± 17	448 ± 23	8 ± 17		8 ± 17	—	—	Wk-20347
Tuvalu	Funafuti Atoll	Cardiidae: *Acrosterigma* (FF)	1896	0.53	–1.53	423 ± 19	459 ± 23	–37 ± 19	—	–37 ± 19	—	—	Wk-19675
Vanuatu Islands	Ambrym Island	Archidae: *Barbatia* sp. (FF)	Oct 1943?	3.49	–2.44	529 ± 30	462 ± 23	67 ± 30	$\chi^2_{1:0.05}$ = 1.76<3.84	29 ± 10	1.76	29 ± 28	Wk-21982
	Espiritu Santo	Coral: *Diploastrea heliopara*	1953	—	—	494 ± 10	469 ± 24	25 ± 10					AA-series
	Ambrym Island	Tellinidae: *Tellina linguafelis* (DF)	1943	2.46	–2.28	660 ± 80	462 ± 23	198 ± 80	Excluded from further consideration because deposit-feeding species				Wk-8384

[a] Diet preferences (in brackets): FF = filter feeder; C = carnivore; DF = deposit feeder; H = herbivore.

[b] Where possible, we have attempted to gain an idea of potential age range of the marine shells sampled. Venerids may live for >40 yr (Beesley et al. 1998:356); Mytilidae, Pectinidae, Ostreidae, Spondylidae, Cardiidae generally live <10 yr (Beukema 1989; Creese et al. 1997:230; Estabrooks 2007; Flood 2007:8), Chamidae (no information): Isognomonidae (no information). Some large species of Pteriidae (e.g. *P. margaritifera*) may live for ~25 yr (Haws 2002:10) and lifespans of up to 46 yr has been recorded for some species of Archidae (Stern-Pirlot and Wolff 2006). Because mollusk shells are built up over their entire life, the margins of the shell will be younger than the hinge. In all cases, we have sampled no more than 5 "circuli." (Circuli are concentric ridges formed on the surface of bivalve shells by the periodic addition of material to the edge of the shell. They become crowded together at the annuli [Almeida and Sheehan 1997] and should not be confused with annuli.) Growth rings (or annuli) on the surface of bivalve shells represent periods of growth cessation, which are often interpreted as yearly rings associated with changing season. However, they can be caused by a variety of environmental and biological causes, and their annual relationship is less certain in locations without seasonal extremes (Jones 1989). Therefore, when calculating the marine modeled age for these shells we have assumed that the carbon was fixed into the shells close to the year of collection. The limited data available for reef gastropods suggests that most live >5 yr and some may reach 20 yr of age (Frank 1969:247). Where necessary, we have interpolated between the 5-yr increments in the Marine04 ages (Hughen et al. 2004).

[c] Lab prefixes: Wk = Waikato Radiocarbon Dating Laboratory; CAMS = Lawrence Livermore National Laboratories; AA= University of Arizona; ANU – Australian National University; L = Lamont-Doherty.

[d] Data calculated from $D^{14}C$ information presented by Burr et al. (2006).

[e] Shells sent from New Caledonia in 1876; therefore, collection date considered robust (personal communication from Phillippe Bouchet to M Phelan, December 1998).

[f] Museum documentation gives island location as "Marutea." We have interpreted this as Marutea Sud since Seurat visited here around this time (Seurat 2003).

From each of these shells, we removed a 5-mm cross-section perpendicular to the edge across multiple increments of growth to avoid intrashell variations in ^{14}C (cf. Culleton et al. 2006) and provide an average value over a maximum period of 5 yr (i.e. 1 increment in the Marine04 data set). This should avoid errors introduced by the variable lifespan of different shellfish species, but also avoid seasonal fluctuation in stable isotope values (Keith et al. 1964). Samples were washed in dilute HCl to remove surface contamination. They were then reacted with orthophosphoric acid and CO_2 converted to graphite at the Waikato Radiocarbon AMS facility, and compressed into a target for analysis at the National Isotope Centre, GNS Science, Wellington. δ^{18}O and δ^{13}C values were measured on gas splits taken during preparation of samples for accelerator mass spectrometry (AMS) analysis at the University of Waikato using a Europa Scientific Penta 20-20 isotope ratio mass spectrometer. For each of the ^{14}C results, the ΔR for a specific location "(s)" was calculated from using the formula Rs(t) – Rg(t) = R(s), where (R(s)) is the difference between the global average (Rg(t)) and the actual ^{14}C activity of the surface ocean at a particular location (Rs(t)) at that time. Each individual ΔR standard error is calculated by the formula $\Delta R\sigma = \sqrt{(\sigma_{Rg(t)}{}^2 + \sigma_{Rs(t)}{}^2)}$ (Stuiver et al. 1986). We have chosen not to apply any correction for fossil fuel input (Suess 1955) to the ΔR values presented in this paper on the basis that the regional and global surface ocean act in parallel to atmospheric forcing (Reimer et al. 2002).

Even when samples are carefully selected according to the prerequisites listed above, there are a number of uncertainties in ΔR values associated with the postulated time of carbon uptake before collection and the influence of diet, habitat, and short-term fluctuation in the water masses. When calculating the amount of uncertainty introduced by the non-uniform ^{14}C content of the shellfish when combining several ΔR values for a region, the standard approach has been to calculate the scatter σ in the unweighted mean (i.e. the empirical standard deviation = $\sigma/\sqrt{n}$) and compare this to the weighted mean, taking the larger of the 2 as the ΔR uncertainty (±) following the recommendations of Stuiver et al. (1986:982). Reimer and Reimer (2006) recently advocated the use of the standard deviation (σ) as a more accurate assessment of ΔR variability. Alternatively, we have calculated the weighted mean for each island group (Table 1) using the χ^2 test to evaluate the internal variability in a group of ΔR values (cf. Ward and Wilson 1978). If the group has additional measurement variability (as indicated if $\chi^2/(n–1)$ is >1), an additional uncertainty is calculated and applied to the ΔR. This additional uncertainty is calculated by $\sqrt{(s^2_{\Delta R pooled} + \sigma^2_{ext})}$, whereby the external standard deviation (σ_{ext}) is determined by subtracting the ^{14}C measurement variance from the total population variance and obtaining the square root (e.g. $\sigma_{ext} = \sqrt{(\sigma^2_{pop} - \sigma^2_{meas})}$) (see Bondevik and Gulliksen in Mangerud et al. 2006:3241–2 for explanation). When $\chi^2/(n–1)$ is ≤1, the weighted mean is used.

RESULTS AND DISCUSSION

We have obtained ΔR values for 31 pre-AD 1950, known-age shell samples from the South Pacific (Table 1). An additional 22 ΔR values have previously been reported (see Petchey [in press] for references). Unfortunately, many of these published ΔR values are of herbivores or deposit-feeding shellfish. We have excluded ΔR values measured on deposit feeders from further analysis, but ΔR values on herbivores from locations dominated by volcanic geologies have been included for consideration (Tables 1 and 2). Figure 1 shows the geographic origin of these samples grouped into 18 regions covering about 300 km radius. We have not been able to locate any additional pre-AD 1950 historic shells from Easter Island, Pitcairn, or the Marquesas and only 1 value was obtained from the Tongan Archipelago and Vanuatu Islands. Large gaps also remain throughout the South Pacific in areas with small isolated atolls. Despite gaps in the data, the evaluation of extant ΔR values (Petchey, in press) in combination with these 31 new ΔR values provides greater insight into marine reservoir variation in the South Pacific.

Table 2 Sample locations showing underlying geology.

Island group	Specific location	Island type*[a]	Reference
Austral Islands	"Tubai islands"	Volcanic islands (minor limestone present on Rapa, Rurutu, and Rimatara are encircled by makatea[b])	Chubb 1927
Easter Island	Easter Island	Volcanic island	Baker et al. 1974
Fiji	Kandavu	Volcanic island	Nunn and Omura 1999
	Ono Is. Vambea	Volcanic island	
	Viti Levu, Ellington	Ancient volcanic island (no limestone recorded at Ellington)	Rodda and Band 1966
Gambier Arch.	Mangareva	Volcanic almost atoll* Open: Elevated island atoll tilted slightly resulting in submergence of atoll ring to S and E	Kirch 2004
Marquesas	Nuku Hiva	Volcanic island	Savanier et al. 2003; Chubb 1930
New Caledonia	Presqu'ile Ducos, Noumea	Continental bedrock island (minor limestone present at all locations)	Lillie and Brothers 1970; Paris 1981
	Poindimié		
	Paines des Gaiacs		
	Loyalty Is.	Carbonate islands	Guillon 1974
Northern Cook Islands	Manahiki	Coral atoll* Open restricted: Shallow passages occur to the N. Lagoon depth varies.	Wood and Hay 1970
	Penrhyn	Coral atoll * Open: Deep passages on the NE and NW	Wood 1967
Samoan Arch.	Tutuila Island	Volcanic island	Keating 1992
	ʻUpolu Island	Volcanic island	
Santa Cruz /Reef Islands	Reef Island	Limestone island	British Solomon Islands, Dept. of Geological Surveys 1969
	Reef Is., Pilini Is., on coral reef	Unconsolidated island	
	Santa Cruz Is., Vanikoro	Volcanic island	Dennis 1981
Society Islands	Tahiti, Outu Maoro	Volcanic island	Williams 1933
	Moorea	Volcanic island	
	Maupiti	Volcanic almost atoll	Rougerie and Wauty 1993
Solomon Islands	Bouganville	Contintental island	Blake and Miezitis 1967
	Bouganville Teop Is.	Continental island	Hughes et al. 1981
	Vella Lavella Island	Volcanic island	
	Malaita, Fauabu	Continental island	
	Ufa Island, Russell Is.	Volcanic island with makatea[b]	
	Guadalcanal Island	Continental island	
Southern Cook Islands	Aitutaki	Volcanic "almost atoll"	Waterhouse and Petty 1986; Wood 1967
	Rarotonga	Volcanic island (minor limestone)	
	Mangaia	Volcanic island with makatea[b]	

Table 2 Sample locations showing underlying geology. *(Continued)*

Island group	Specific location	Island type*[a]	Reference
Tongan Arch.	Tongatapu	Carbonate island	Roy 1990
	Vava'u Island	Carbonate island	
Tuamotu Arch.	Marutea Sud	Coral atoll* Closed: Water exchange occurs only during storms	Chevalier 1972
	Hao	Coral atoll* Open: 1 narrow pass to N	Salvat (1985)
Tuvalu	Funafuti	Coral atoll* Open: Deep lagoon. Shallow passage is available on the E and W edge of lagoon	Oceandots.com 2008
Vanuatu Islands	Ambrym	Volcanic island	British Government, Ministry of Overseas Development 1976
	Espiritu Santo	Ancient volcanic island (major limestone)	Mallick and Greenbaum 1977; Macfarlane et al. 1983

[a] * = The classification of Open/Closed atoll is based on Salvat (1985) where open and closed mean, respectively, with and without a pass. Additional information is required to assess residence time of water within the lagoon.

[b] Makatea = fossil coral reef.

The region under study is encircled by the South Pacific Subtropical Gyre, a circulatory system driven by the combined effects of the tropical tradewinds and the westerly winds in the subtropical regions. This results in the high-latitude eastward-flowing Antarctic Circumpolar Current (ACC) and the mid-latitude westward-flowing South Equatorial Current (SEC). The SEC transports water from the center of the gyre and bifurcates on the east coast of Australia, feeding both the East Australian Current (EAC) and the New Guinea Coastal Current (NGCC) (Figure 1). This circulatory system is considered to create relatively stable surface water conditions at the center of the gyre (Rougerie and Wauty 1993). The ΔR values presented in Table 1 and Figure 2 are generally low and uniform across the region, in keeping with these observations.

Variation does exist in our data set, however, as indicated by the χ^2 statistics for the Tuamotu Archipelago ($\chi^2_{1:0.05}$ = 4.14<3.84), Southern Cook Islands ($\chi^2_{3:0.05}$ = 102.12<7.81), Fiji ($\chi^2_{3:0.05}$ = 13.06<7.81), and Tongatapu ($\chi^2_{1:0.05}$ = 5.89<3.84) (Table 1). This spread in values signifies non-uniform ^{14}C content in the shellfish, and hints at a more complex picture than previously recognized by researchers utilizing marine samples from the South Pacific for dating purposes. We hypothesize several causes for this variation below.

Ocean Boundaries

At the boundaries of the Pacific Ocean, a complex interplay occurs between ocean currents and the continental landmasses (Figure 1). For example, Petchey et al. (2004) noted large variations in ΔR over short distances in the Bismarck Sea, where seasonal reversals in the SEC and North Equatorial Counter Current resulted in localized upwelling. ΔR variation has also been noted in shells from areas of upwelling along the eastern edge of the Pacific Ocean: along the Californian coastline (Culleton et al. 2006) and the Peru/Chile coastline (Taylor and Berger 1967). Less obvious boundaries can be caused by the interaction of different oceanic current systems. In the South Pacific, there are 3 major changes in water body: the Subtropical Front, Tasman Front, and the Equator. Large fluctuations in ΔR occur at the Galapagos Islands due to Ekman upwelling from the Equator (Taylor and Berger 1967; Druffel et al. 2004) which occurs when the wind-driven component of transport in the surface ocean moves perpendicular to the mean wind stress, causing divergence in the surface water and upwelling of water depleted in ^{14}C (Tomczak and Godfrey 2001:41). Further south, the boundary between Subtropical and Antarctic water (Subtropical Front) forces ^{14}C-depleted water upwards just off the east coast of the South Island of New Zealand and along the southern flank of the Chatham Rise, resulting in high and variable ΔR values (Petchey et al. 2008). Lower ΔR values have been recorded for islands located in the Tasman Front (Norfolk and Kermadec Islands), which are attributed to high air-sea ^{14}C exchange and heightened absorption of atmospheric CO_2 associated with enhanced biological production in the rich waters of the front (Petchey et al. 2008).

Disturbance to the dominant water flow by island chains impinging on the oceanic currents may also result in significant ΔR variation. Petchey (in press) has speculated that oceanic conditions around the Hawaiian Islands may, in part, be responsible for some of the variation observed by Dye (1994) (ranging from –29 ± 4 to 280 ± 80 ^{14}C yr). Interaction between the Hawaiian Island chain and northeasterly tradewinds result in upwelling and downwelling in the lee of the islands, as well as the formation of large-scale eddies formed in the 25 cm s^{-1} flow of the North Equatorial Current. Petchey et al. (2004) have also hypothesized that variable ΔR values for the Solomon chain of islands were caused, in part, by the disturbance of the SEC creating localized eddies and wakes (Figure 2). This observation is supported by research into surface chlorophyll variability in this region (Messié and Radenac 2006). Large-scale eddies have also been documented along the southeast coastline of Australia at the boundary between warm water of the Coral Sea and the cooler water of the Tasman Sea (Tomczak and Godfrey 2001:126–8), and around the east coast of New Zealand (Ridgway and Dunn 2003). The surface currents around the Marquesas are also strong enough to create zonal currents and fluctuating eddies (Martinez and Maamaatuaiahutapu 2004) and seasonal variation has been recorded (Signorini et al. 1999:3122), but additional values from the Marquesas are needed to evaluate the true extent of any variability.

Given that ΔR variation can be caused by disruption to the ocean currents, variable ΔR should be expected for the Fiji, New Caledonian, and Vanuatu island chains. These islands impinge on the SEC, dividing the southern branch into 3 main jets: South Caledonian Jet (SCJ), North Caledonian Jet (NCJ), and North Vanuatu Jet (NVJ) (Ganachaud et al. 2007) (see Figure 1). The NVJ is fairly broad (with a slow flow of 10 cm s^{-1}).[7] The NCJ, on the other hand, is narrow and speeds of more than 20 cm s^{-1} are reached at the northern tip of New Caledonia (Gourdeau et al. 2008), causing eastward flows that may generate an eddy field in the lee of the island. These conditions also result in the development of dominant currents on the eastern side of New Caledonia and upwelling on the southwest coast (Ganachaud et al. 2007:20) analogous to that recorded for the Hawaiian chain of islands. The combined effect of zonal jets and island interaction with the Southeast Tradewinds also creates weak eastward flowing currents in the lee of Vanuatu (i.e. Coral Sea Countercurrent) and Fiji (i.e. Fiji Basin Countercurrent) along 16°S and 18°S, respectively, with enhanced eddy variability in these regions (Qiu et al., in press). Available oceanographic data is currently too limited to outline the full extent of surface ocean conditions in these regions.

A total of 4 ΔR values are now available for Fiji, providing an average value of 11 ± 26 ^{14}C yr ($\chi^2_{3:0.05} = 13.06<7.81$) (Table 1). Two of the values come from Viti Levu; the other 2 ΔR values are from the offshore islands of Kandavu (Tevuki) and Ono Island, Vabea. Within this data set, the

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[7] Swift flows in excess of 20 cm s^{-1} are necessary to form eddies or wakes around the islands (Andrews and Pickard 1990; Heywood et al. 1990).

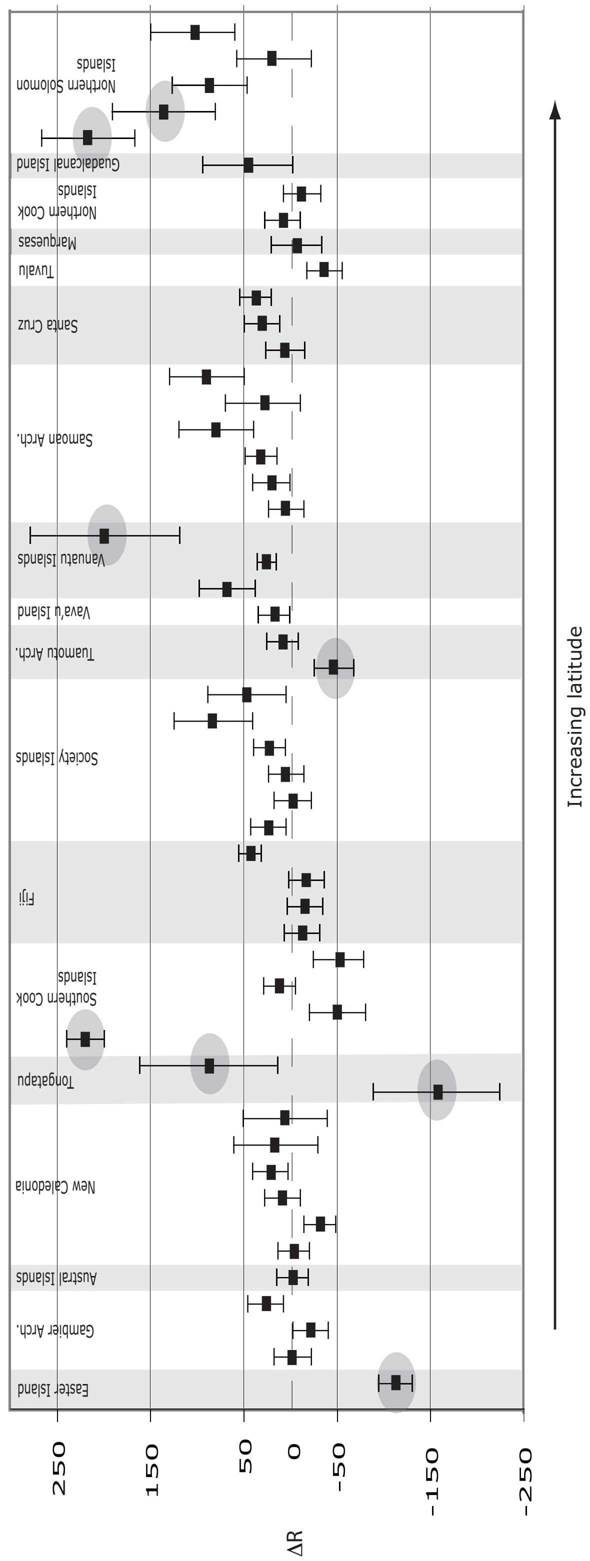

Figure 2 Plot of ΔR values given in Table 1 by latitude. Grayed circles indicate ΔR values that are considered unreliable (see text for details).

ΔR outlier is a value of 43 ± 12 ^{14}C yr from coral core data published by Toggweiler et al. (1991). Without further information on the precise collection location for this particular sample, it is impossible to know if this value is a function of localized upwelling associated with variability in the currents around the islands. Conversely, a combined ΔR for the 6 values from New Caledonia and "Loyalty Island" result in a value of –3 ± 9 ^{14}C yr with no external variance ($\chi^2_{5:0.05}$ = 5.03<11.07) (Table 1). This is unexpected given the observations outlined above. It is possible that the extensive barrier reef extending either site of New Caledonia protects the enclosed lagoon, creating a more uniform environment. We think it is likely, therefore, that additional marine shells from New Caledonia may give anomalous ^{14}C results especially at the northern extent of the island or where the barrier reef is patchy. Limited data is available from the Vanuatu Islands and precludes evaluation of the regional Vanuatu ΔR at this time.

Habitat Effect

In the central zone of the gyre, the flows are weak (about 5–10 cm s^{-1}) (Rougerie and Rancher 1994). Theoretically, any variation to ΔR should therefore be predominantly caused by habitat-specific influences, many of which will have a small geographic range. Such influences include the incorporation of carbon derived from peat, dissolved (i.e. hardwaters) or particulate carbonates derived from calcareous bedrock (Keith et al. 1964; Dye 1994; Spennemann and Head 1998) and volcanic activity, all of which result in high ΔR values. Lower ΔR values have been attributed to the incorporation of freshwater derived from riverborne dissolved and particulate organic matter or rainfall (Stuiver and Braziunas 1993; Dye 1994; Southon et al. 2002), high air-sea ^{14}C exchange coupled with reduced mixing with older subsurface waters (Guilderson et al. 2000), heightened absorption of atmospheric CO_2 associated with enhanced biological production (Petchey et al. 2008), and increased wind and wave action (Forman and Polyak 1997:888; Hogg et al. 1998).

Hardwater

Hardwaters contain large amounts of bicarbonate ions, which are generated by seepage through calcareous strata. Organisms that live within these hardwaters indirectly take up ^{14}C derived from those strata. Consequently, shellfish that inhabit environs within a limestone catchment may yield a ^{14}C age that is excessively old (Dye 1994; Petchey et al. 2008). Spennemann and Head (1998) suggested a ΔR of 87 ± 74 ^{14}C yr from Havelu Lagoon, Tongatapu, was caused by waters draining through Pliocene and Pleistocene limestone. Although the precision of this particular value limits further evaluation of this hypothesis, an anomalous value for Mangaia Island in the Southern Cook Islands (ΔR = 219 ± 20 ^{14}C yr) is almost certainly caused by uptake of ^{14}C from the limestone bedrock (Table 2). Mangaia is composed of a central volcanic core surrounded by an almost continuous ring of Pleistocene limestone cliffs (makatea) (Waterhouse and Petty 1986). All streams on the island drain through underground channels in the raised limestone and many discharge as springs at the coast (Wood 1967). The δ^{13}C value for Wk-21062 from Mangaia (–0.95‰) is more depleted than the typical range (0.9‰ and 2.1‰) for modern South Pacific surface-ocean dissolved inorganic carbon (DIC) (Gruber et al. 1999; Tagliabue and Bopp 2008: Figure 2) (see also Havelu [ANU-6420], which has a δ^{13}C of –0.25‰).[8] However, any input of freshwater should result in the depletion of both δ^{13}C and δ^{18}O, which does not seem to be the case for Wk-21062 (Keith et al. 1964:1781; Gat 1996:241,

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[8] Most shellfish precipitate their shells in equilibrium with the stable isotopes in the local environment, but some may display an offset because of metabolic or kinetic effects (i.e. growth rate) (Keith et al. 1964; Goewert et al. 2007). A difference in δ^{18}O between calcite and aragonite has also been noted in some shellfish (Rick et al. 2006), but this has been attributed to differential equilibrium conditions between the interior and exterior of the shell rather than shell chemistry (Keith et al. 1964; Kirby et al. 1998). Because of the nature of sampling in this study, this interior bias should not be present.

255; Culleton et al. 2006:390). A second ΔR value from Mangaia gave a ΔR result of –51 ± 30 ^{14}C yr, which is in keeping with a value of –52 ± 27 ^{14}C yr for a coral core sequence from Rarotonga, and a second Rarotonga shell ΔR value of 11 ± 17 ^{14}C yr (*Pinctada margaritifera*). With the anomalous Mangaia Island value of 219 ± 20 ^{14}C yr excluded from the Southern Cook Island average, the 3 remaining values are statistically indistinguishable ($\chi^2_{2:0.05}$ = 5.66<5.99) (Table 1).

The impact of hardwaters on ^{14}C only becomes significant in areas where the water exchange with the open ocean is restricted, such as enclosed lagoons or estuaries, resulting in long residence times (i.e. the time a parcel of water remains in a lagoon). The presence of limestone in a particular region is not, therefore, an automatic guarantee of anomalous ΔR results (McKinnon 1999:94). In the case of Vava'u Island, blocks of ancient limestone are tilted to the south, resulting in a dissected drowned coastline. This enables the interior waterways to have a connection to the open sea and prevents the freshwater becoming saturated in $CaCO_3$ (Roy 1990). Consequently, the ΔR value of 17 ± 17 ^{14}C yr presented in Table 1 is not anomalous when compared to the other South Pacific values (Figure 2). In non-tilted islands, such as Tongatapu, however, a drop in sea level has created an enclosed, non-circulating water body that is supersaturated with dissolved carbonate (Roy 1990).

In many instances, limited information about sample provenance prevents further evaluation of the impacts of hardwater and limestone ingestion by shellfish. We suggest that selection of shell samples from geological or archaeological contexts from such islands is potentially risky and may poorly reflect the age of the samples being dated. Unfortunately, there are few islands in the Pacific where ancient raised coral limestone is not present to some degree (Table 2). The fact that the majority of islands covered in this research are well washed by ocean currents is probably responsible for the limited number of anomalous ΔR values observed.

Brackish Water (POC)

Anomalous marine shell ^{14}C results may also be caused by the ingestion of particulate terrestrial organic matter (either modern or derived from ancient peat or soil) (Keith et al. 1964). This effect, however, tends to be restricted to suspension-feeding shell species that are known to tolerate brackish water conditions (cf. Kaneohe Bay, O'ahu Island, Hawai'i, where the shellfish *Macoma dispar*— common in areas of freshwater discharge—gave an anomalous ΔR value of –479 ± 120 ^{14}C yr [Dye 1994]). Of the shellfish listed in Table 1, Chamidae, Pteriidae, Archidae, Pectinidae, and Ostreidae prefer full-strength, clear seawater and will quickly die if exposed to brackish or freshwater for long periods (Beesley et al. 1998). Some species of Mytillidae and Isognomonidae do, however, occupy brackish environs and can feed on particulate organic matter from a terrestrial source (Beesley et al. 1998:249, 264). Marine shellfish that incorporate a significant proportion of carbon derived from plant or soil sources should exhibit δ^{13}C values lower (about –5 to –10‰) than that of 100% marine environments because the decay of C3 plant material and soil processes depletes δ^{13}C (Keith et al. 1964). All shells listed in Table 1 contain stable carbon isotope abundances (δ^{13}C) that fall within or above the typical range of surface ocean DIC (see above), confirming their dependence on marine carbon (Stuiver and Polach 1977:358).

Volcanic Activity

Volcanic activity has also been suggested as a possible cause of elevated ΔR values because of the release of gas depleted in ^{14}C (Petchey et al. 2004, 2008). Shells from 2 active volcanoes in the Pacific have been analyzed: Ambrym Island and Raoul Island. Although Raoul Island is an active volcano with multiple eruptions occurring within the last 1000 yr (Lloyd and Nathan 1981:9), variation between ΔR results of different shellfish was found to be minor. Redating of a suspension-feeding species (this research) from Ambrym Island enables comparison with a previous result given by Petchey et al. (2004) of a deposit-feeding shellfish (ΔR = 198 ± 80 ^{14}C yr), which may have been influenced by Pliocene and Pleistocene limestone sands from islands 10 km away. Ambrym is a basaltic island formed by an active shield volcano known for violent phreatic eruptions (McCall et al. 1970). The new ΔR value of 67 ± 30 ^{14}C yr is higher than the typical South Pacific values presented here (Figure 2), but indistinguishable from the published ΔR value of 25 ± 10 ^{14}C yr for coral from Espiritu Santo (Burr et al. 1998) ($\chi^2_{1:0.05}$ = 1.76<3.84; see Table 1). Limited data for the Vanuatu Islands precludes any further assessment, and factors other than volcanic activity may be responsible for the elevated ΔR value (e.g. island chain effect, or incorrect date of collection since this could not be independently verified). It is apparent from research into the influence of geothermal activity on ^{14}C (Rubin et al. 1987, Sveinbjörnsdóttir et al. 1992; Pichler et al. 1999) that any effect from volcanic activity tends to be highly localized. Consequently, this remains as a potential cause of anomalies in shell ΔR in areas with active volcanic fissures.

Lagoons and Reefs

Little is known about the effect lagoon or shallow reef environments have on the marine ^{14}C content of shellfish. These environments often incorporate both marine and freshwater aspects that, if sufficiently isolated from the wider oceanic circulation, can result in a unique ^{14}C signature. Ultimately, this will depend on the number and orientation of channels (hoas[9] and passes) that enable water exchange into the lagoon, prevailing winds and currents, as well as the geomorphology and height of any surrounding reefs. In lagoons where there is limited exchange with the open ocean, water exchange relies primarily on interstitial and atmospheric sources (Andréfouët et al. 2001:401), which can result in ΔR extremes such as that documented for the lagoon of Reao Atoll (eastern Tuamotu Archipelago). Reao is a “closed atoll” where exchange with open ocean water occurs via shallow hoa (Salvat 1985). Pirazzoli et al. (1987:66) found that the ^{14}C activity of live corals from within the lagoon was in equilibrium with the atmosphere, while coral from the outer reefs was in equilibrium with seawater (i.e. a difference in apparent age of around 400 yr) (no ^{14}C values are presented by Pirazzoli et al. [1987]; therefore, they are not included in Table 1). From our data set, only Marutea Sud (Tuamotu Archipelago) is classified as a closed lagoon whereby exchange with the open ocean only occurs during storms (Chevalier 1972) (Table 2). The depleted ΔR value of –47 ± 21 ^{14}C yr for Marutea is in keeping with this hypothesis and very different from the ΔR of 8 ± 17 ^{14}C yr for shell collected from the reef on Hao Atoll within 30 km of Marutea ($\chi^2_{1:0.05}$ = 4.14<3.84) (Table 1). Negative values also occur elsewhere in the Pacific in situations where water exchange should be more open (e.g. a ΔR value of –37 ± 19 ^{14}C yr for *Acrosterigma* from Funafuti Atoll, which is classified as an “open” atoll), but since considerable variation in water residence time has been recorded across lagoons (e.g. Atkinson et al. 1981), significant differences in ΔR should be expected.

Additional complications to shellfish or coral ^{14}C determinations may be caused by wind and wave action augmenting the transfer of enriched $^{14}CO_2$ from the atmosphere resulting in a more negative ΔR value (cf. Forman and Polyak 1997; Hogg et al. 1998). This has been suggested as a cause for the anomalous ΔR of –157 ± 68 ^{14}C yr for a sample of *Anadara antiquata* from the islet of Pangaimotu (Petchey, in press). This islet, offshore from Tongatapu, is surrounded by a shallow reef flat and is exposed regularly at low tide (Richmond and Roy 1986). Enhanced biological production within fertile lagoons environments may also enrich the ^{14}C and δ^{13}C of these waters, as has been suggested

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[9] Shallow passages enabling water exchange with the open ocean are called “hoas.” “Passes” are deeper channels that are navigable (Charpy and Dufour 2008).

for depleted ΔR values for Norfolk Island (average ΔR = –49 ± 10 ^{14}C yr) (Petchey et al. 2008). Consequently, there is no reliable ΔR value for Tongatapu.

Negative ΔR values are common in our data set: e.g. Easter Island[10] (–113 ± 18 ^{14}C yr); Tearia Bank (Gambier Archipelago) (–22 ± 19 ^{14}C yr); Poindimié (NC) (–32 ± 17 ^{14}C yr); Mangaia (–51 ± 30 ^{14}C yr); Rarotonga (–52 ± 27 ^{14}C yr); Marutea Sud (Tuamotu Archipelago) (–47 ± 21 ^{14}C yr); Funafuti Atoll (–37 ± 19 ^{14}C yr); and the Fijian samples from Kadavu (–13 ± 19 ^{14}C yr), Ono Island (–16 ± 19 ^{14}C yr), and Ellington (–18 ± 19 ^{14}C yr) (Figure 1 and Table 1). Unfortunately, museum documentation is insufficient in most cases to assign the shellfish to lagoon, atoll, or reef environments; moreover, the conditions encountered in any of these environments can vary widely even over short distances.

CONCLUSION

This research has provided 31 new ΔR values for the South Pacific region. This has enabled an evaluation of ΔR by island group and has highlighted a number of potential problems when dating marine shells from Pacific Islands, including the potential impact of large island chains disturbing the surface water flow and the possibility of atolls and lagoons isolating water from the larger ocean reservoir. The most significant impact on ΔR value, however, occurs in regions with limestone geology where there is either direct ingestion of limestone by the shellfish or uptake of waters depleted in ^{14}C. On the basis of these results, a preliminary regional ΔR value has been calculated for each of the island groups that make up New Caledonia (–3 ± 9 ^{14}C yr), Southern Cook Islands (–15 ± 31 ^{14}C yr), Fiji (11 ± 26 ^{14}C yr), the Society Islands (17 ± 24 ^{14}C yr), Vanuatu (29 ± 28 ^{14}C yr), the Samoan Archipelago (28 ± 26 ^{14}C yr), Northern Cook Islands (–2 ± 14 ^{14}C yr), Santa Cruz Islands (26 ± 11 ^{14}C yr), and northern Solomon Islands (66 ± 31 ^{14}C yr) (Table 1). Of these values, there are limited data for the Vanuatu and Tongan archipelagos. This is of particular concern as these regions are of significant importance to understanding initial human colonization of the Pacific (Burley et al. 1999; Bedford et al. 2006), but are dominated by large areas of exposed limestone (Table 2).

Paleoclimate reconstructions using banded coral core records have indicated that there is long-term temporal marine ^{14}C reservoir variability in some regions of the Pacific, which are tied to periods of climate change (Dunbar and Cole 1996:5; Druffel and Griffin 1993). Fluctuation in sea levels over time in response to climate change is also well documented for the South Pacific islands (Pirazzoli and Montaggioni 1988; Yonekura et al. 1988; Dickinson et al. 1999; Moriwaki et al. 2006). Although climate change will have an influence on the wider marine reservoir, as documented by the coral core records, the impact to the more restricted environs inhabited by many marine shellfish could potentially be of greater significance. Examination of variation in the marine reservoir over time is vital, therefore, if marine shell is to be used to establish chronological control over issues of island colonization and cultural change (Allen 2006; Nunn et al. 2007a,b), or the evaluation of coastal geomorphology and climate change (Yonekura et al. 1988; Moriwaki et al. 2006). The available banded coral core records are, however, few in number, geographically restricted, and may not be subject to the same environmental, and therefore reservoir, conditions as shellfish. Archaeological studies using contemporaneous marine/terrestrial samples (Yoneda et al. 2001; Deo et al. 2004; Ascough et al. 2005) have also demonstrated the importance of longer-term ΔR evaluation. Unfortunately, there are only a handful of published ΔR values calculated from archaeological marine/ter-

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[10] Of 5 coral cores collected from around Easter Island, only 1 exhibited distinct annual growth bands suitable for chronology development (Core Ovahe -97-1). This is attributed to the location of Easter Island at the environmental limits of coral tolerance (Beck et al. 2003; Mucciarone and Dunbar 2003:117, 122) and necessitates caution when using this ΔR value.

restrial pairs from the South Pacific. Moreover, the reliability of these values is currently hindered by problems of association and material suitability (Petchey and Addison 2008). In an attempt to correct this shortcoming, paired marine/terrestrial samples have been selected from archaeological sites of varying age from the Cook Islands, Marquesas, Fiji, and Tongan and Samoan archipelagos. These data are now under analysis.

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Appendix 1 Available information for samples analyzed for ΔR.[a]

Island group	Museum acquisition no.*	Collector(s)*	Provenance*	Latitude/ longitude	Sample material*	Date*	Est. time elapsed from death to collection (yr)[b]	Confirmation of collection date	Lab # (Wk-)
Austral Islands	AK:81247	AT Pycroft	“Tubai Islands”	Islands centered on 23°26′S, 149°28′W	*Isognomon legumen*	1932	0	Pycroft toured the Pacific on the mission steamer Southern Cross in 1932 (Pycroft 1935)	20349
Fiji	NMNZ: 20003460	N Gardner	“Kandavu,” Tevuki	19°02′S, 178°23′E	*Fragum unedo*	Apr 1952(?)	<5	Probably Norm Gardner. Served in the Pacific during WWII, therefore collection date no earlier than 1939 (Conchologists List Archives 2006)	21057
	AM: C061255	T Dranger	Ono Is, “Vambea”	18°55′S, 178°29′E	*Conus achatinus*	1933	<5	Dranger worked in the Pacific between 1924 and 1935 (Schwengel 1957)	21058
	NMNZ: 200012118	WRB Oliver	Viti Levu, Ellington	17°21′S, 178°13′E	*Chama* sp.	Oct 1919	<5	Oliver visited a number of Pacific islands at the end of WWI (Dell 2005)	21056
Gambier Arch.	AM: C119180	LG Seurat	Mangareva Atoll, Vaiatekeue Is., 3.6-m coral rocks	23°04′S, 134°54′W	*Pinctada maculata*	Feb 1903	<5	Seurat was undertaking research in French Polynesia until 1905 (Seurat 2003)	19677
	AM: C028221		Mangareva Atoll	23°08′S, 134°58′W	*Pinctada margaritifera*	Sep 1903	<5		19678
	PM[c]		Tearia Bank 18 m.	23°05′S, 134°56′W	*Chama pacifica*	Nov 1904	<5		21061
New Caledonia	AM: C449013	J Brazier	Presqu’ile Ducos, Noumea	22°16′S, 166°27′E	*Gafrarium tumidum*	1903/4(?)	5<10	Date questionable; Brazier collected specimens for the Australian Museum from New Caledonia in 1865 and 1873; he sold part of his collection to Museum post-1893 (McMichael 1969)	20336

Appendix 1 Available information for samples analyzed for ΔR.[a] *(Continued)*

Island group	Museum acquisition no.*	Collector(s)*	Provenance*	Latitude/ longitude	Sample material*	Date*	Est. time elapsed from death to collection (yr)[b]	Confirmation of collection date	Lab # (Wk-)
	AM: C103837	J Kerslake	Poindimié	20°56′S, 165°20′E	*Laevichlamys squamosa*	Apr-Aug 1950	<5	Kerslake visited New Caledonia in May-August 1950 (Ponder and Child 1986)	20341
	NMNZ: 20003520	RK Dell	Paines des Gaiacs	21°20′S, 165°00′E	*Tapes litteratus*	July 1943	<5	Dell was stationed in New Caledonia during WWII (Davidson 2002)	21055
	AK:3408	Hartley	Loyalty Isands	Islands centered on 21°01′S, 167°E	*Conus arenatus*	1926(?)	<5	No information available	21059
Northern Cook Islands	NMNZ: 200012095	P Marshall	"Manahiki"	10°24′S, 161°01′W	*Fragum fragum*	1924	<5	Employed from 1924 by the New Zealand Public Works Department; wrote paper (Marshall 1927) on geology of Mangaia (Watters 2006)	19676
	AM: C057434	GP Whitley	Penrhyn atoll	9°01′S, 158°03′W	*Pinctada margaritifera*	1931	<5	Whitley joined staff of the Australian Museum in 1922 (Murray and Roach 2002); published "A day in Rarotonga" (Whitley 1933)	19691
Samoan Islands	AM: C061233	T Dranger	"Fagaitua," Tutuila	14°17′S 170°36′W	*Fragum fragum*	1933	<5	Dranger visited Samoa in 1925 and remained in the Pacific until 1935 (Schwengel 1957)	19682
	AM: C015564	J Brazier	"Pango Pango" Harbour, Tutuila	14°16′S 170°42′W	*Antigona reticulata*	Jul 1865	<5	Brazier was on the cruise of HMS *Curaçao* to Samoa in 1865 (McMichael 1969)	19683
	NMNZ: 20003454	RW Tate	Fagaloa, Western Samoa	13°32′S 171°30′W	*Fragum fragum*	1922	<5	Col. R Tate was New Zealand's administrator in Samoa 1919–1923 (Campbell 1997)	20343

Appendix 1 Available information for samples analyzed for ΔR.[a] *(Continued)*

Island group	Museum acquisition no.*	Collector(s)*	Provenance*	Latitude/ longitude	Sample material*	Date*	Est. time elapsed from death to collection (yr)[b]	Confirmation of collection date	Lab # (Wk-)
Santa Cruz Islands	AM: C052139	E Troughton and AA Livingston	Reef Island, on a sand cay	Islands centered on 10°15′S, 166°20′E	*Fragum fragum*	Jul-Aug 1926	1	Australian Museum expedition to Santa Cruz Islands in 1926 (Whitley 1975)	19689
	AM: C332539		Reef Islands, “Pilini” Island, On coral reef	10°10′S, 166°15′E	*Isognomon purna*		0		21065
	AM: C052163		Vanikoro	11°40′S, 166°58′E	*Beguina semiorbiculata*		<5		20344
Society Islands	NMNZ: 200012227	WRB Oliver	Tahiti, Outu Maoro	17°33′S, 149°37′W	*Barbatia* sp.	Jun 1919	1	Oliver visited Tahiti at the end of WWI (Dell 2005)	19684
	NMNZ: 20003186		Tahiti, Taravao, under stones	17°42′S, 149°20′W	*Arca decissata*	Jul 1919	1		19685
	NMNZ: 200018180		Tahiti, Taravao	17°42′S, 149°20′W	*Isognomon* sp.	Jul 1919	0		20348
	NMNZ: 200012289		Papeete	17°32′S, 149°34′W	*Drupa ricinus*	Jun 1919	0		21060
Southern Cook Islands	NMNZ: 20006312	HE Fyfe	Mangaia, reef	21°54′S, 157°58′W	*Drupa ricina conus*	1954(?)	<5	Probably Horace E Fyfe, head geologist of the New Zealand Geological Survey; no further info	21062
	NMNZ: 2000012274	P Marshall	Mangaia	21°54′S, 157°58′W	*Drupa ricinus*	1924	<5	Employed from 1924 by the New Zealand Public Works Dept.; wrote paper in 1927 on the geology of Mangaia (Watters 2006)	21983
	AM: C374444	GP Whitley	Rarotonga	21°14′S, 159°46′W	*Pinctada margaritifera*	Oct/Nov 1931	<5	Whitley published “A day in Rarotonga” in 1933	20340

Appendix 1 Available information for samples analyzed for ΔR.[a] *(Continued)*

Island group	Museum acquisition no.*	Collector(s)*	Provenance*	Latitude/ longitude	Sample material*	Date*	Est. time elapsed from death to collection (yr)[b]	Confirmation of collection date	Lab # (Wk-)
Tonga Arch.	AM: C011554	J Brazier	Vava'u Island	18°36′S, 174°20′W	*Isognomon isognomon*	Jul 1865	<5	Brazier was on the cruise of HMS *Curaçao* to Samoa in 1865 (McMichael 1969)	20346
Tuamotu Arch.	AM: C119073	LG Seurat	Marutea Atoll	21°32′S, 137°55′W	*Pinctada margaritifera*	Dec 1903	<5	Seurat was undertaking research in French Polynesia until 1905 (Seurat 2003)	19690
	PM[c]		Hao, on reef	18°15′S, 140°54′W	*Spondylus pacificus*	Nov 1904	<5		20347
Tuvalu	AM: C391203	C Hedley	Funafuti Atoll	8°31′S, 179°13′E	*Acrosterigma biradiatum*	1896	5–10	Hedley took part in the Royal Society of London expedition to Funafuti Atoll in 1896 (Smith 2007)	19675
Vanuatu Islands	AK[c]	GE Inglis	"Ambrin," New Hebridies	16°15′S, 168°7′E	No species given	Oct 1943(?)	<5	Presented to Museum in Oct 1943; no further info	21982

[a] * = Data obtained from museum labels (PM = Museum of Natural History, Paris; AM = Australian Museum; AK = Auckland Museum; NMNZ = National Museum of New Zealand). Because "Date" may refer to date of acquisition, we have obtained independent verification of collection date where possible.

[b] Estimated time elapsed from death to collection base on visible condition of shell; 0 = presence of animal remains indicating live collection; 1 = fresh ligament or complete peristrocium; <5 = desiccated ligament or worn peristrocium; 5<10 = no ligament, but fresh appearance and valve in articulation suggesting close association (not recommended).

[c] No museum acquisition number available.